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USAAVLABS TECHNICAL NOTE 4

SUITABILITY OF A DRAG SPHERE ANEMOMETER FOR MEASUREMENT OF VTOL AIRCRAFT DOWNWASH

By

Russell O. Stanton

June 1970

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

U S ARMY MATERIEL COMMAND

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House Task AA 68-10
USAAVLABS Technical Note 4
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SUMMARY

Tests were conducted on a simple, low-cost drag sphere anemometer to determine its suitability for measuring wind velocities in the vicinity of VTOL aircraft and helicopters. A drag sphere anemometer is a device for determining wind velocity by measuring the drag force acting on a spherical body of known drag coefficient.

The drag sphere anemometer, as tested, was found to be capable of measuring wind velocities and direction in one plane over a speed range of 10 to 110 mph. Instrumentation accuracy was found to be ± 2.5 mph in the speed range of 10 to 50 mph and ± 7% in the speed range of 50 to 110 mph. Directional accuracy was found to be approximately ± 30° at low wind speeds, ± 10° for speeds from 30 to 60 mph, and ± 5° above 60 mph. On the basis of the relatively unsophisticated tests performed, the drag sphere anemometer is considered to be suitable for measurement of downwash velocities in close proximity to hovering VTOL aircraft. If required, the upper end of the usable speed range could be extended through additional wind-tunnel calibration.

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INTRODUCTION

Downwash is a universal problem of concern to the designers and users of all VTOL aircraft, helicopters included. This problem has grown in interest with the advent of higher disc loading VTOL aircraft such as the tilt-wing, lift-fan, and lift-jet. In order to study the downwash problem, the flow-field velocities must be determined, preferably for a full-scale aircraft. The use of full-scale aircraft requires a large number of velocity sensors to ensure adequate coverage of the area. To obtain useful information, the following instrument system characteristics are considered to be necessary: speed range, 15 to 150 mph; speed accuracy, ± 5%; directional accuracy, ± 10° in a given plane; virtually simultaneous readings from all sensors; portable; and relatively inexpensive.

Five presently available instrumentation systems were studied to determine which would meet the stated requirements: (1) sonic anemometer, (2) hot-wire anemometer, (3) meteorological anemometers, (4) swiveling pitot-static tubes, and (5) pitot-static tube arrays. The sonic anemometer and hot-wire anemometer were found to be technically suitable, but costly. Information on the accuracy and cost of these two systems is given in Table I. The meteorological anemometers and swiveling pitot-static tubes do not appear to be satisfactory based on previous downwash testing conducted with the XC-142A at Eglin AFB.[1] The pitot-static tube arrays would be inaccurate since a pitot-static tube must be aligned with the flow direction; however, the flow field around a hovering VTOL aircraft is turbulent, with flow direction changing constantly.

A search was then made for an instrument that could be fabricated in-house and would be technically and financially suitable. An instrument which appeared to satisfy all the requirements was a drag sphere anemometer. This instrument consists of a perforated, hollow sphere mounted on a two-axis strain-gaged balance beam. The drag force acting on the sphere is measured by the balance beam, and by determining the drag coefficient of the sphere, the wind velocity can be calculated. This report gives the results of suitability tests on such a drag sphere anemometer.

TABLE I. ACCURACY AND COST DATA FOR THREE SUITABLE SYSTEMS

Anemometer System	Speed Accuracy	Maximum Directional Accuracy	Estimated Cost* ($)
Drag Sphere	± 7% above 50 mph ± 2.5 mph below 50 mph	Variable(Fig. 12)	1,000
Sonic (data obtained from Cambridge Sys)	± 3% above 30 mph ± 1 mph below 30 mph	± 6°	13,500
Hot Wire (data obtained from Flow Corp)	± 2% above 75 mph ± 1.5 mph below 75 mph	± 4°	18,500

*The cost given is for one three-dimensional sensor, excluding an oscillograph recorder, which would be common to all systems.

DESCRIPTION OF DRAG SPHERE ANEMOMETER

The drag sphere anemometer (Figure 1) is a device for determining wind velocity by measuring the drag force on a sphere. For this application, a design based on a simplified NASA prototype[2] was used. This drag sphere anemometer uses a Cosom Saf-T-Play ball for the sphere. This ball, which is made in the form of a 3.7-inch-diameter thin plastic shell, has twenty-six 5/8-inch-diameter holes in the shell to stabilize the flow around the sphere, thus suppressing the lateral oscillations present with a smooth, closed sphere and causing the resultant force to act through the center of the sphere. The drag force is measured on a simple, two-axis, strain-gaged balance beam. This beam is shielded from the wind by 1-inch-diameter tubing, so that the only drag force measured is that of the sphere. Each strain-gage bridge-axis set (Figure 2) consists of four active arms, each arm being a Budd 314-T-350 strain gage, with a maximum allowable bridge voltage of 10 VDC. The bridge output is displayed on a recording oscillograph. No amplifiers are needed when CEC 339 galvanometers are used in the oscillograph.

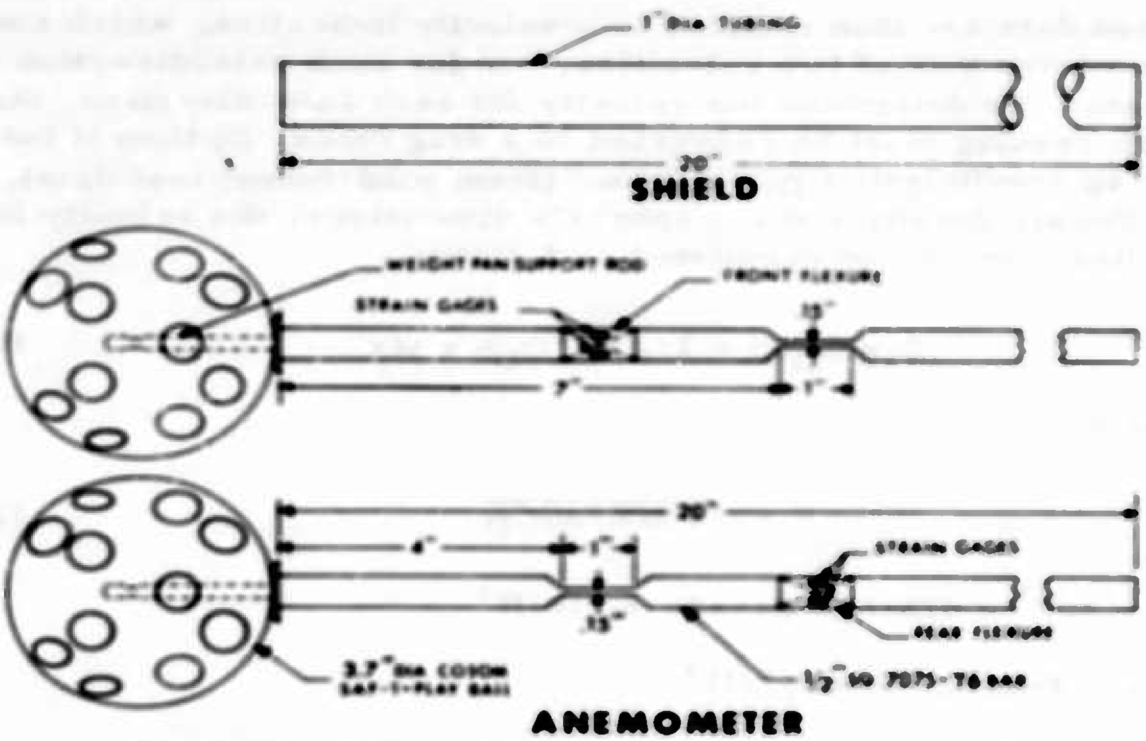

Figure 1. Drag Sphere Anemometer Assembly.

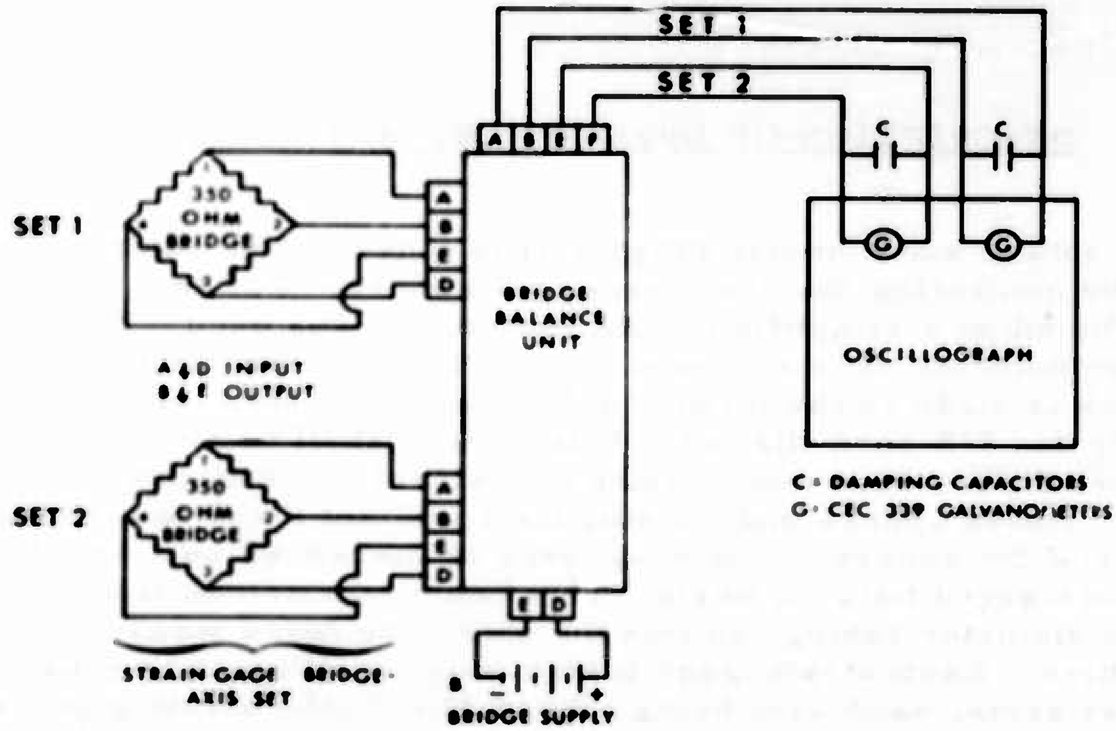

Figure 2. Two-Axis Strain-Gage Balance Schematic.

The recorded data are then reduced to a velocity indication, which consists of the vector sum of two velocities, one for each axis-direction of the load beam. To determine the velocity for each axis-direction, the oscillograph reading must be converted to a drag force, D; then if the sphere's drag coefficient, C_D, is known (from wind-tunnel test data), along with the air density and the sphere's dimensions, the velocity for each axis-direction can be calculated as follows:

$$D = C_D qS = 1/2 \rho V^2 C_D S = MX \qquad (1)$$

which leads to

$$V = \sqrt{2\, MX/\rho S C_D} \qquad (2)$$

where $q = 1/2 \rho V^2$ - dynamic pressure, lb/ft^2

ρ = air density, $lb\text{-}sec^2/ft^4$

S = area of circle corresponding to the outside diameter of this sphere, ft^2

M = slope of load versus oscillograph deflection curve, lb/in.

X = oscillograph deflection, in.

V = wind velocity, ft/sec

During the early testing, it became apparent that the mechanical oscillations of the beam were too large to allow accurate readings and that some form of damping was necessary. Damping was achieved by inserting a large (4000 μfd) capacitor across the input to the oscillograph.

A support stand (Figure 3) was constructed for field trials. This stand, simulating a telescoping stand, was used to evaluate support vibration and anchoring problems that might be encountered. A 6-foot instrument height was selected, as it is the maximum expected to be used in an actual downwash velocity investigation and would present the most serious vibration problem.

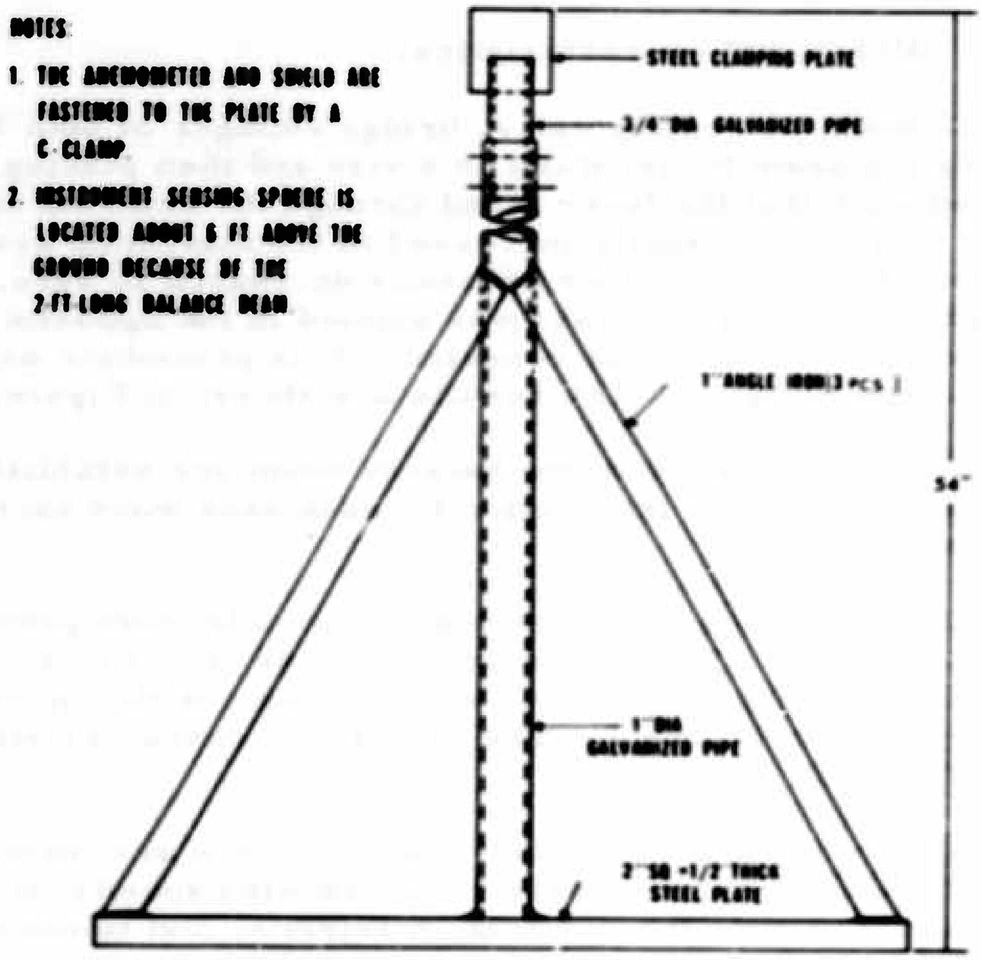

Figure 3. Support Stand.

CALIBRATION OF DRAG SPHERE ANEMOMETER

The drag sphere anemometer was calibrated in two steps:

1. A load calibration of the strain-gage beam to determine:

   a. Characteristics of force-versus-oscillograph curve.

   b. Directional characteristics and interactions.

2. A wind-tunnel calibration[2] of the drag sphere to determine:

   a. Characteristics of the force-versus-dynamic-pressure curve.

   b. Directional characteristics.

The balance beam was calibrated at bridge voltages of both 3 and 5 VDC by clamping the beam horizontally in a vise and then placing weights in a pan attached such that the force acted through the centroid of the sphere. The weight was incrementally increased to the maximum available oscillograph deflection and then incrementally decreased to zero. The beam was rotated 180° so that the load was applied in the opposite direction, and the loading procedure was repeated. This procedure was used to calibrate all the flexures. The results are shown in Figures 4 and 5.

Directional characteristics of the balance beam are established, in part, by noting that there is no interaction between axes when each axis is loaded separately.

Wind-tunnel test data on this sphere are available from previous tests conducted by NASA[2]. These data are shown as drag force versus dynamic pressure in Figure 6 and as sphere drag coefficient versus Reynolds number in Figure 7. The directional characteristics are plotted in Figure 8.

Equation (2) shows that for constant ρ and S, there are three parameters that will affect the accuracy of the recorded wind speed: M, C_D, and X. Figures 4 and 5 provide the nominal, maximum, and minimum values of M. Figure 6 provides the maximum, nominal, and minimum values of C_D. The reading accuracy of the oscillograph trace determines the

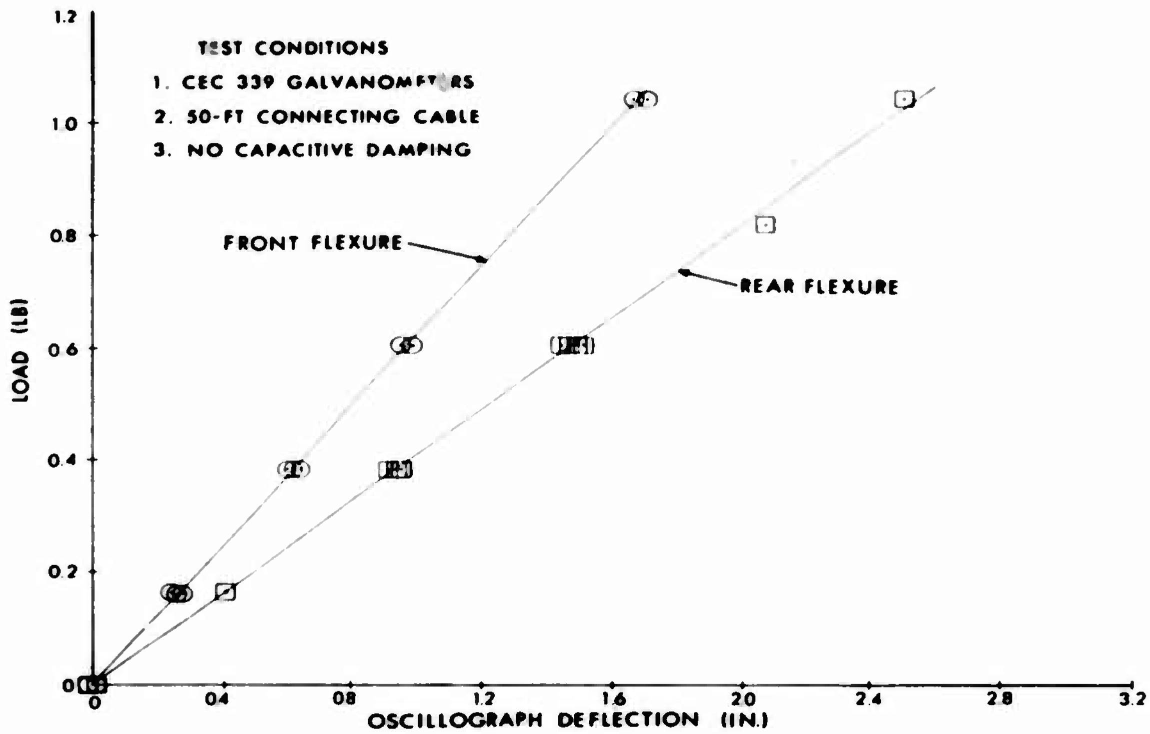

Figure 4. 3-VDC Load Calibration.

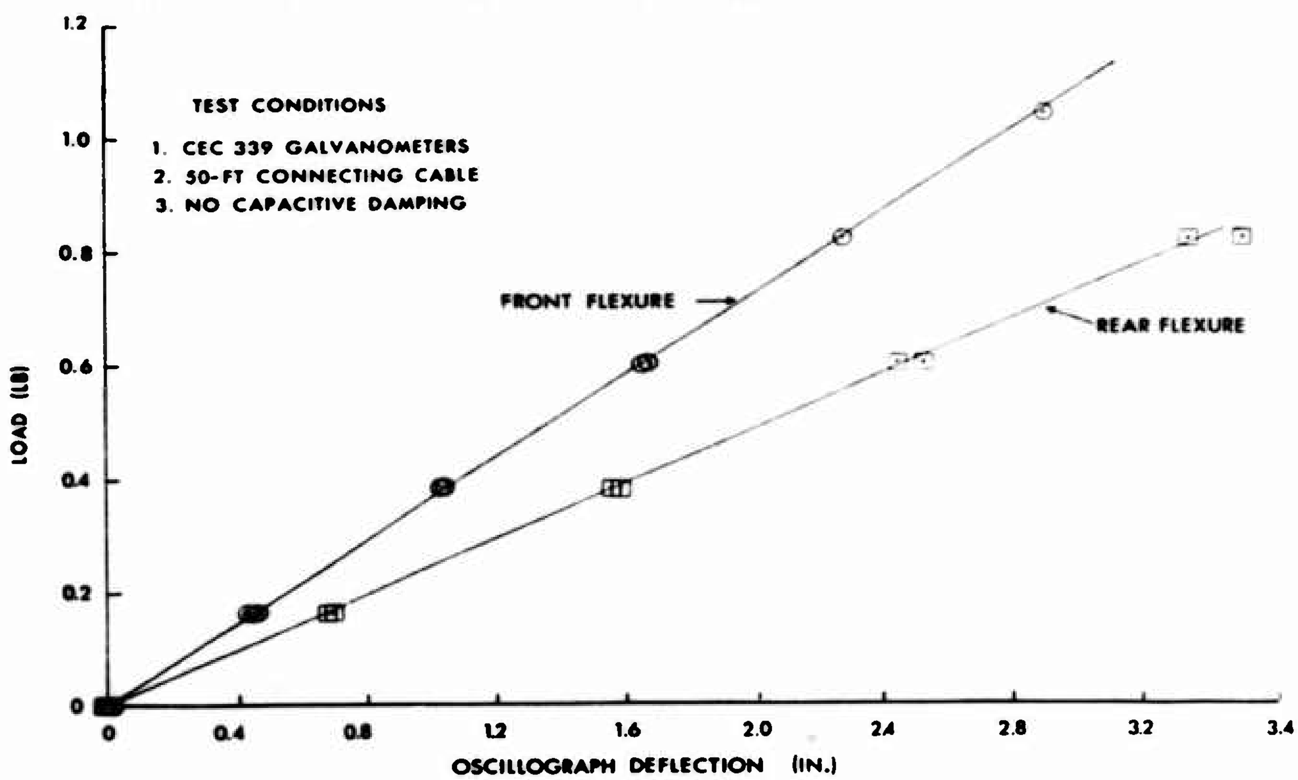

Figure 5. 5-VDC Load Calibration.

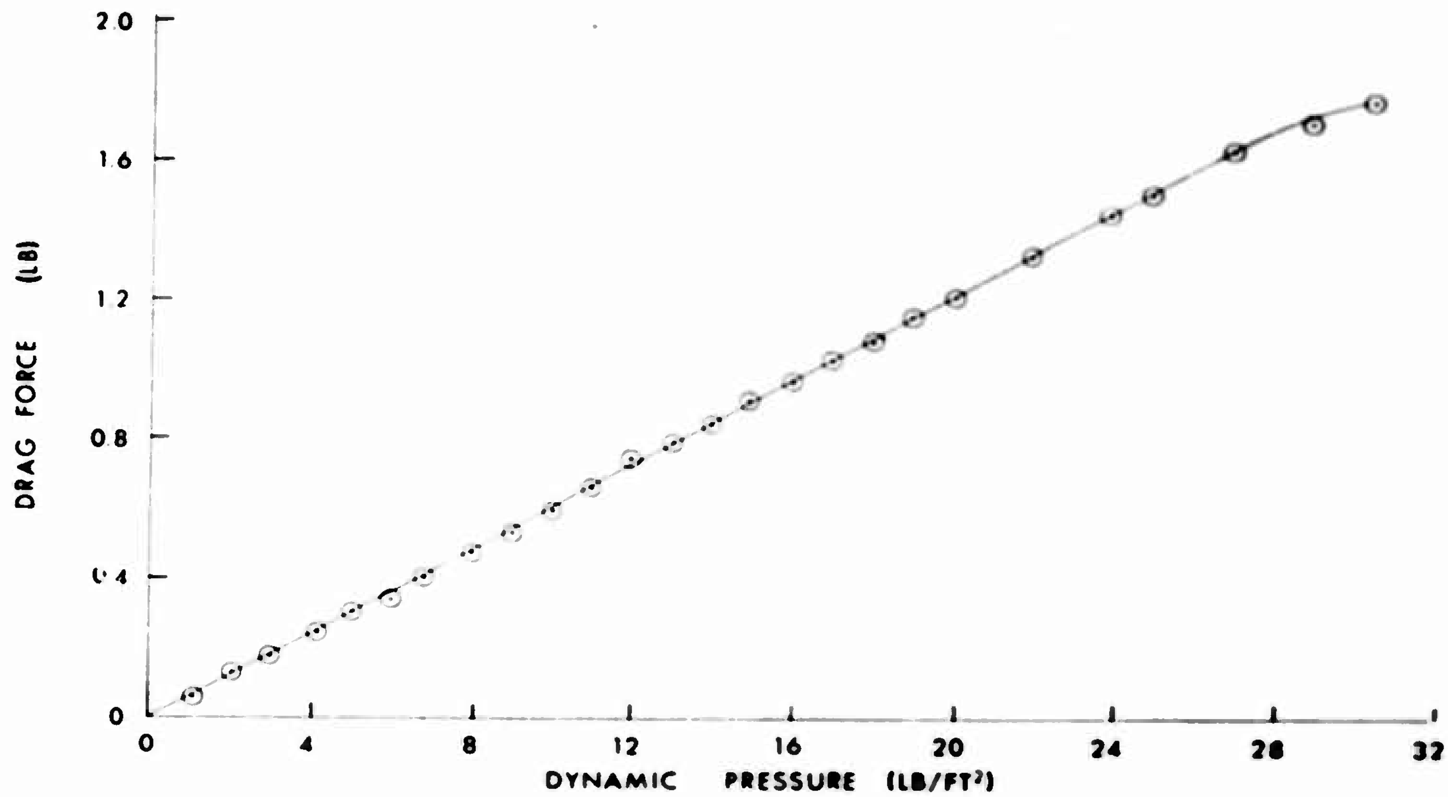

Figure 6. Drag Force Versus Dynamic Pressure (Reference 2).

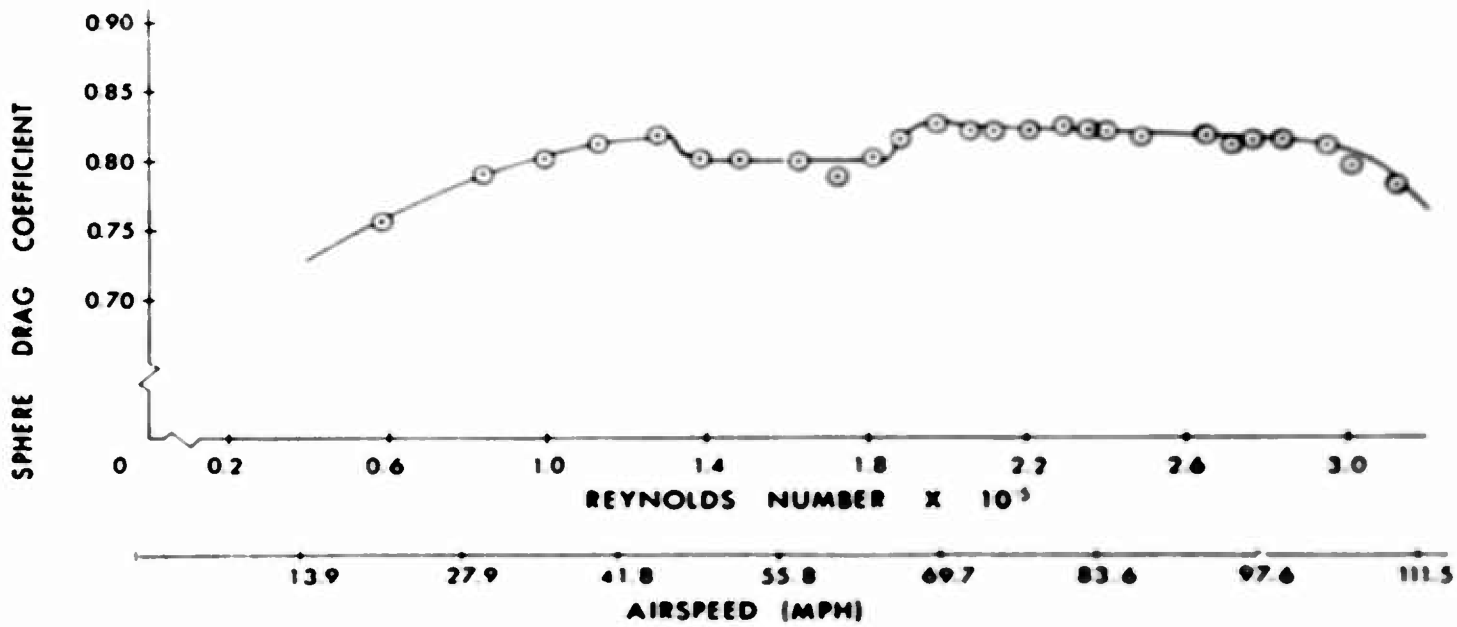

Figure 7. Drag Coefficient Versus Reynolds Number (Reference 2).

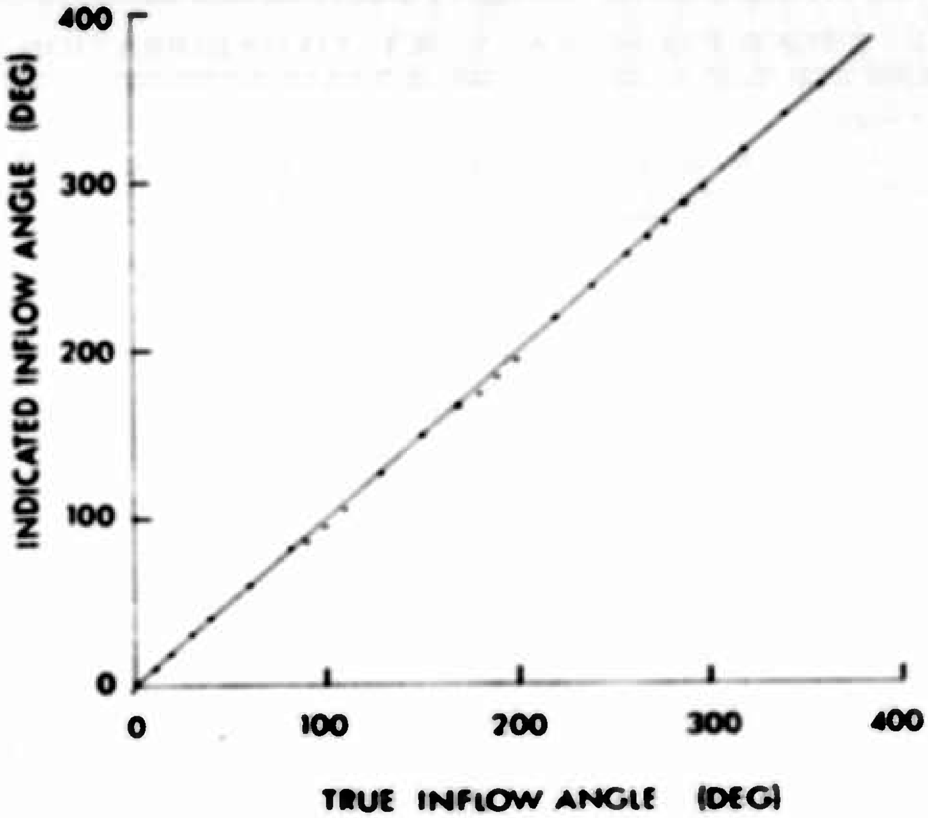

Figure 8. True Inflow Angle Versus Indicated Inflow Angle.

variation in X; this accuracy, obtained using an Oscar S-2 reader, is normally considered to be ± .02 inch. However, an accuracy of ± .01 inch can be obtained using manual rather than machine data reduction techniques.

Equation (2) also shows that if the maximum M is used in conjunction with the minimum C_D, a maximum speed will result for a given X. Likewise, if the minimum M is used in conjunction with the maximum C_D, a minimum speed for a given X will result. These three values for speed (nominal, maximum, and minimum) are presented in Table II. One must also consider the effect of the reading accuracy, which is combined with the effects of variations in M and C_D and presented in Table III and Figures 9 and 10 (for both front and rear flexures). Based on a study of several flow angle conditions, it was determined that the maximum resultant velocity error will occur for a 45° flow angle. This maximum possible error is extracted from Table III and plotted in Figure 11. These data are presented for the two reading accuracies mentioned in the preceding paragraph.

TABLE II. SPEED INACCURACY DUE TO CALIBRATION ERROR						
Flexure	Bridge Voltage (VDC)	$V_{Nominal}$ (mph)	$V_{Minimum}$ (mph)	$V_{Maximum}$ (mph)	ΔV (mph)	ΔV (pct)
F	3	20.1	19.4	21.5	-.7 1.4	-3.5 7.0
R	3	16.3	15.7	17.0	-.6 .7	-3.7 4.3
F	5	15.4	14.8	16.5	-.6 1.1	-3.9 7.1
R	5	12.5	12.2	13.0	-.3 .5	-2.4 4.0
F	3	63.4	60.9	68.1	-2.5 4.7	-3.9 7.4
R	3	51.3	50.0	53.8	-1.3 2.5	-2.5 4.9
F	5	48.3	47.0	51.7	-1.3 3.4	-3.0 7.0
R	5	39.5	38.8	40.9	-.7 1.4	-1.8 3.5
F	3	89.7	86.4	96.1	-3.3 6.4	-3.7 7.4
R	3	72.9	70.6	76.1	-2.3 3.2	-3.2 4.4
F	5	68.6	66.2	73.3	-2.4 4.7	-3.5 6.9
R	5	56.0	54.6	57.9	-1.4 1.9	-2.5 3.4
F	3	110.0	106.0	117.0	-4.0 7.0	-3.6 6.4
R	3	89.0	86.4	95.2	-2.6 6.2	-2.9 7.0
F	5	84.1	81.5	89.5	-2.6 5.4	-3.1 6.4
R	5	68.7	66.8	71.0	-1.9 2.3	-2.8 3.3

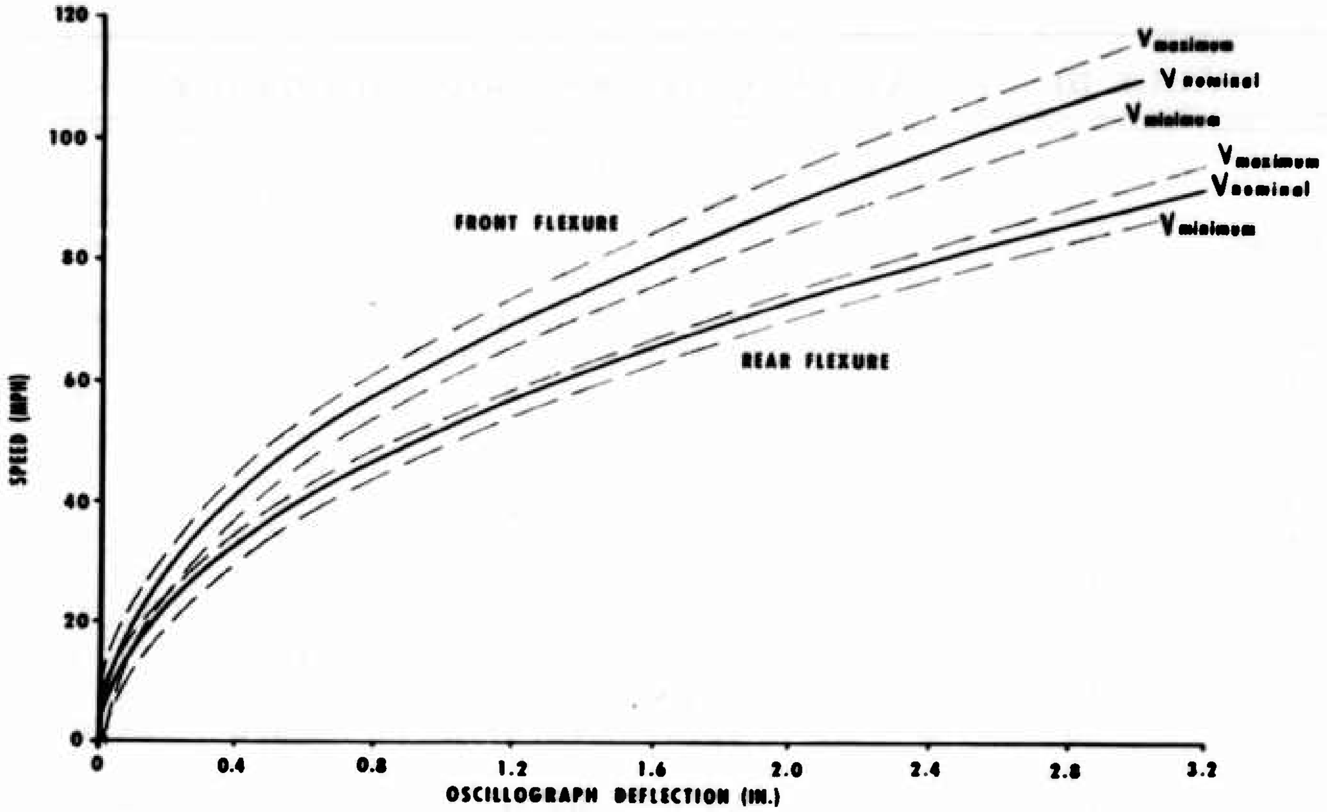

Figure 9. 3-VDC Speed Calibration.

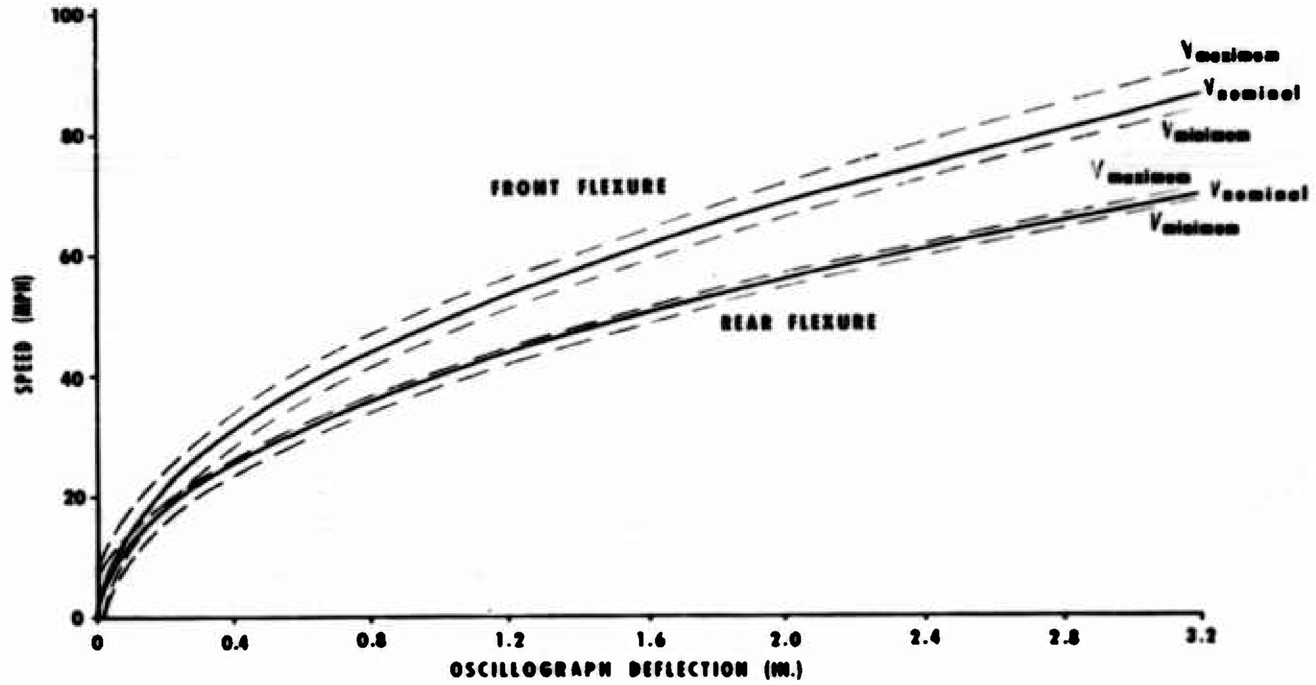

Figure 10. 5-VDC Speed Calibration.

TABLE III. TOTAL VELOCITY READOUT ACCURACY						
	True		± .02 Inch Reading Accuracy		± .01 Inch Reading Accuracy	
Bridge Voltage (VDC)	Rear V_1 (mph)	Front V_2 (mph)	Rear V_1 (mph)	Front V_2 (mph)	Rear V_1 (mph)	Front V_2 (mph)
3	90	90	86.4	85.8	86.5	85.9
3	80	80	77.0	76.0	77.1	76.2
3	70	70	67.2	66.2	67.3	66.4
3	60	60	57.4	56.5	57.5	56.6
3	50	50	47.6	46.7	47.7	46.9
3	40	40	37.7	36.8	38.0	37.1
3	30	30	27.7	26.9	28.0	27.5
3	20	20	17.9	17.9	18.1	19.0
3	10	10	7.0	7.0	8.7	8.7
3	0	0	-6.5	-6.5	-5.0	-5.0
5	70	70	69.0	67.9	69.1	68.1
5	60	60	59.0	58.0	59.1	58.1
5	50	50	49.1	48.0	49.2	48.2
5	40	40	39.1	38.1	39.2	38.3
5	30	30	29.3	28.1	29.7	28.7
5	20	20	19.2	18.2	19.5	18.8
5	10	10	8.1	7.5	9.3	9.0
5	0	0	-5.5	-7.5	-4.0	-5.0

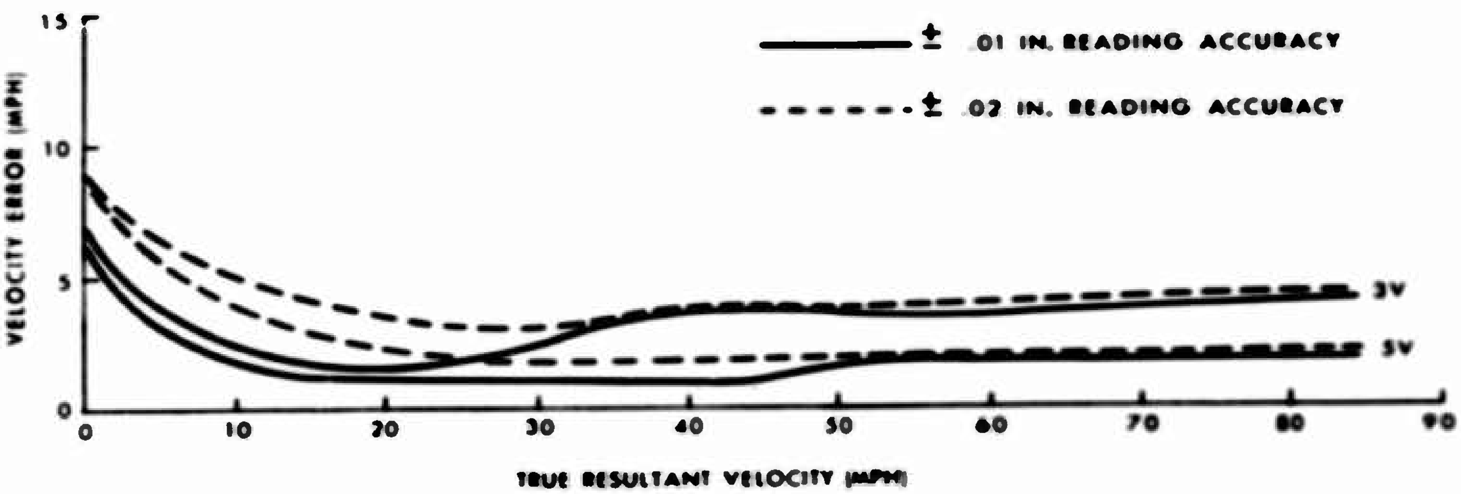

Figure 11. Maximum Possible Velocity Error.

Since direction is calculated using the two speed components, the inaccuracies in speed will result in an inaccurately calculated direction. It can be seen that the greatest inaccuracy occurs at a true angle of 0°, which results in the rear flexure's sensing the entire downwash velocity and thus operating in a region of minimal velocity error, while the front flexure senses none of the velocity and is thus operating in a region of maximum velocity error. This directional inaccuracy is presented in Figure 12, with the data extracted from Table III.

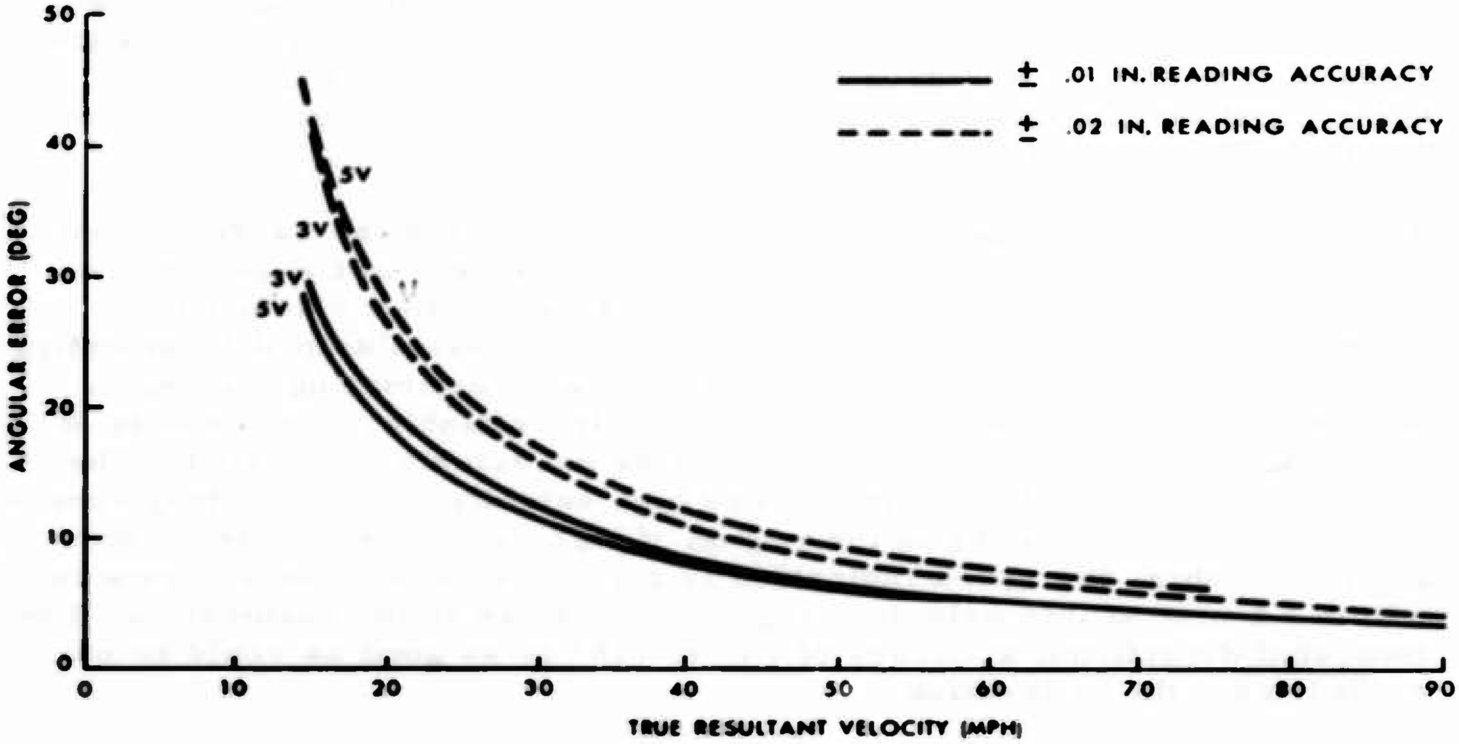

Figure 12. Maximum Possible Angular Error.

SUITABILITY TESTING

Three tests were conducted to determine the suitability of the drag sphere anemometer for measuring downwash velocities in the vicinity of VTOL aircraft and helicopters. First, a 30-inch-diameter shop fan was used as a laboratory check of the response of the instrument to an airflow. The velocity indication was compared with the readings of a hot-wire anemometer. Second, a field test was performed to check the functional aspects of the drag sphere anemometer in field use. Third, the capacitive damping was checked to determine its effects, if any, on the time-averaged signal.

The test using the 30-inch-diameter fan covered only the narrow speed range of approximately 10 to 20 mph. A comparison of the two indications is given in Table IV. The direction assigned to the hot-wire anemometer indication is approximate, since it was obtained by orienting the probe for a maximum reading and "eyeball"-estimating the angle. No other means of measurement was readily available. The results of the test support the calibration accuracies previously calculated. The fan is not capable of producing a very high velocity; thus, the drag sphere anemometer is operating in the region of high reading error (± 4 mph). In spite of this, the speed indication is generally seen to be accurate to within ± 4 mph at this velocity range, as is shown in the calibration. The indicated directional accuracy of +4° to -15° is as good as could be expected from the calibration.

To determine the suitability of the instrument in actual use, the drag sphere anemometer and its support stand were placed in the vicinity of a hovering UH-1 helicopter. The instrument was located approximately 40 feet from the rotor center, at an angle of 30° to the right of the longitudinal axis, and 6 feet above the ground. The stand was held in place with three sandbags; an additional sandbag was used to secure the cable leading to the oscillograph. The UH-1 hovered at a skid height of about 2 feet. The hover attitude was not stable because of a gusty tail wind; therefore, no attempt was made to determine the actual velocity, but the signal characteristics were determined as shown in Figure 13. These results show that the instrument system can function in a satisfactory manner and that usable data can be obtained. The mounting system performs adequately, and any mechanical vibrations that are present are damped out by the capacitor. The only oscillations present in the reading appear to be caused by the nonsteady nature of the flow (Figure 13).

TABLE IV. COMPARISON OF HOT-WIRE ANEMOMETER AND DRAG SPHERE ANEMOMETER

Hot-Wire Anemometer		Drag Sphere Anemometer		Velocity	Directional
Velocity (mph)	Direction (deg)	Velocity (mph)	Direction (deg)	Error (pct)	Error (deg)
19.0	255	22.6	240	15.9	-15
19.0	210	23.1	213	17.7	-3
20.5	170	21.9	155	6.4	-15
15.9	170	16.3	156	2.4	-14
15.9	190	15.3	194	-3.9	4
13.3	260	13.3	246	0	-14

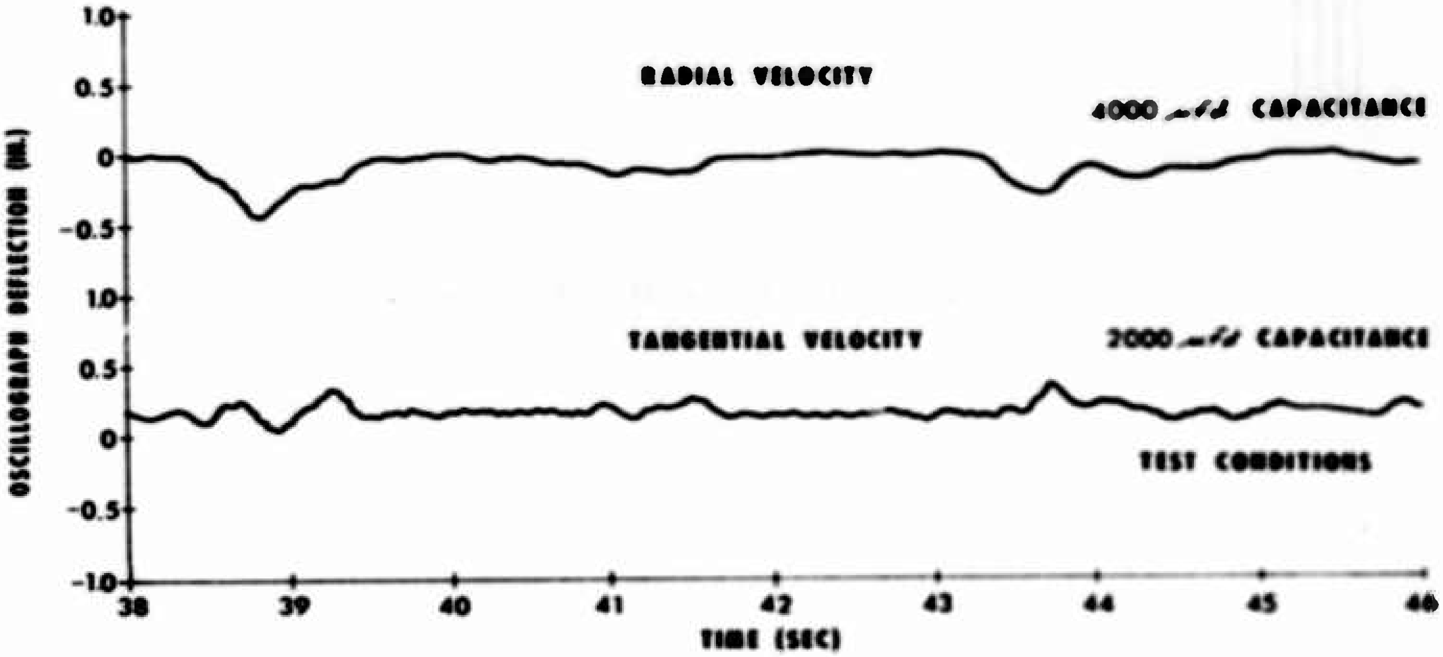

Figure 13. Typical Oscillograph Trace for UH-1 Downwash.

A vibration exciter was used to observe the capacitive damping effects. The exciter consisted of a small DC motor with an eccentric weight mounted on the shaft. The motor was tied to the end of the beam and activated to induce a vibration into the beam. A capacitor was switched in and out of the circuit and its polarity was reversed. The results of this test, shown in Figure 14, revealed that the capacitor had no effect on the time-averaged signal but did effectively eliminate a periodic mechanical vibration.

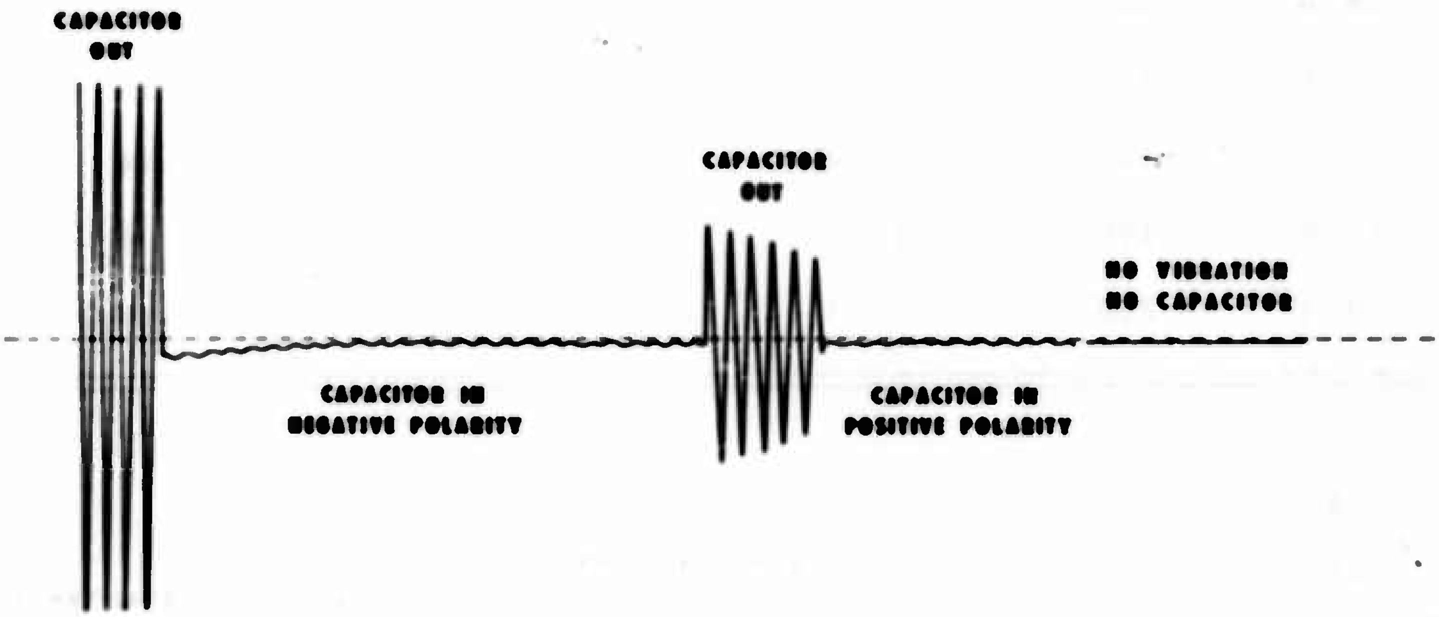

Figure 14. Capacitor Effects.

CONCLUSIONS

It is concluded that:

1. The drag sphere anemometer is suitable for measuring downwash velocity near hovering VTOL aircraft.

2. The speed range of approximately 15 to 110 mph is below the desired 150 mph and is limited only by a lack of wind-tunnel data on the sphere at higher speeds.

3. The speed range can be extended to 150 mph or more by extended wind-tunnel tests.

4. The speed accuracy of the system is satisfactory for measuring downwash velocity; however, particular attention must be given to reading accuracy.

5. The angular accuracy at velocities of less than 30 mph is unsatisfactory for precise measurement.

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2. Fhoughner, Jerome T., Jr., EXPERIMENTAL WIND TUNNEL STUDIES OF DRAG SPHERE TYPE ANEMOMETER, Unpublished NASA Memo, September 1963.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Aviation Materiel Laboratories Fort Eustis, Virginia	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
SUITABILITY OF A DRAG SPHERE ANEMOMETER FOR MEASUREMENT OF VTOL AIRCRAFT DOWNWASH

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Note

5. AUTHOR(S) (First name, middle initial, last name)
Russell O. Stanton

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1970	23	2

8a. CONTRACT OR GRANT NO. NA b. PROJECT NO. House Task AA 68-10 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAVLABS Technical Note 4 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Aviation Materiel Laboratories Fort Eustis, Virginia

13. ABSTRACT

Tests were conducted on a simple, low-cost drag sphere anemometer to determine its suitability for measuring wind velocities in the vicinity of VTOL aircraft and helicopters. A drag sphere anemometer is a device for determining wind velocity by measuring the drag force acting on a spherical body of known drag coefficient.

The drag sphere anemometer, as tested, was found to be capable of measuring wind velocities and direction in one plane over a speed range of 10 to 110 mph. Instrumentation accuracy was found to be ± 2.5 mph in the speed range of 10 to 50 mph and ± 7% in the speed range of 50 to 110 mph. Directional accuracy was found to be approximately ± 30° at low wind speeds, ± 10° for speeds from 30 to 60 mph, and ± 5° above 60 mph. On the basis of the relatively unsophisticated tests performed, the drag sphere anemometer is considered to be suitable for measurement of downwash velocities in close proximity to hovering VTOL aircraft. If required, the upper end of the usable speed range could be extended through additional wind-tunnel calibration.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

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Security Classification

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Downwash						
Anemometer						
V/STOL						
Helicopter						

Unclassified
Security Classification